



AURORA ON GANYMEDE

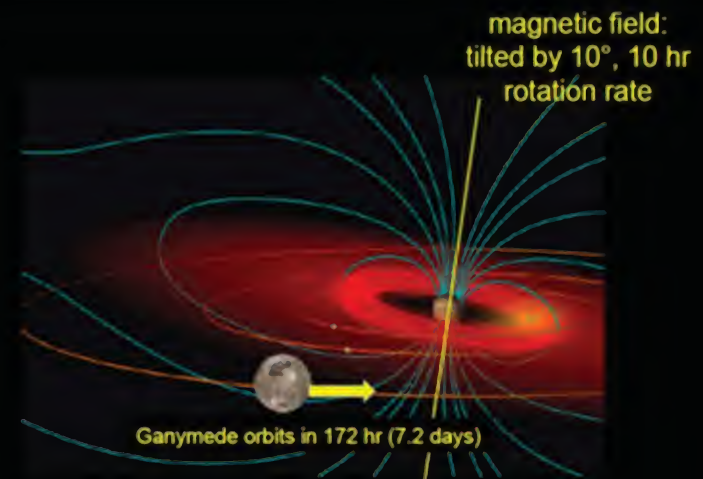
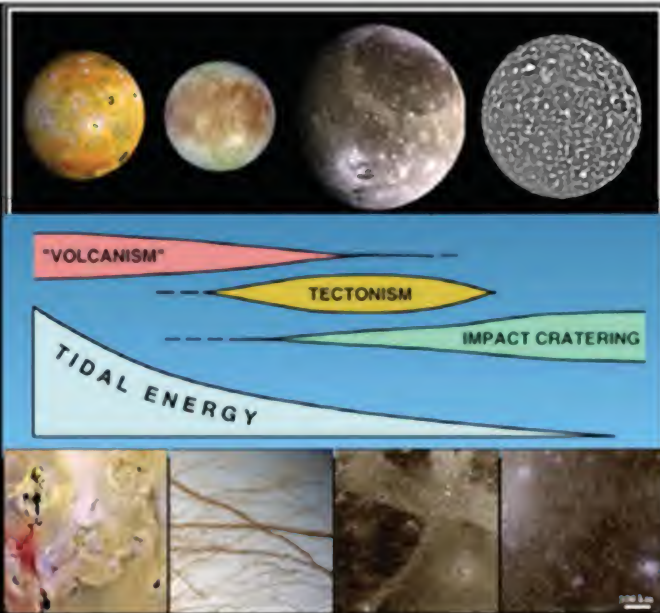
Melissa A. McGrath
NASA Marshall Space Flight Center

Ganymede



The largest satellite in the solar system, larger than Mercury and Pluto, only slightly smaller than Mars

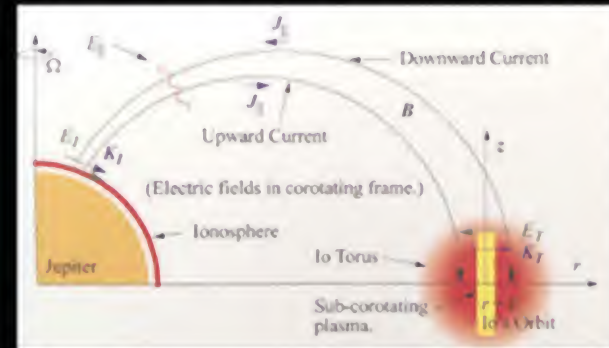
Interior structures greatly clarified by Galileo close flybys



All the Galilean satellites have tenuous atmospheres and associated ionospheres that exhibit a wide range of properties, including surface pressures ranging from picobar (Europa, Ganymede) to nanobar (Io).

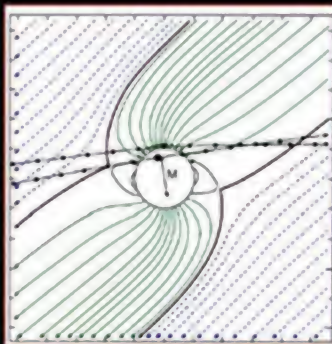
	Io	Europa	Ganymede	Callisto
Primary constituent	SO ₂	O ₂	O ₂	O ₂
P ₀ (nbar)	0.6	7x10 ⁻⁴	7x10 ⁻⁴	0.01-0.1
N (cm ⁻²)	2x10 ¹⁶	5x10 ¹⁴	5x10 ¹⁴	~ 10 ¹⁶ O ₂ 8x10 ¹⁴ CO ₂
Source	Volcanoes/ sublimation	Sputtering/ sublimation	Sputtering	Sputtering/ meteorites?

Satellites with atmospheres and ionospheres immersed in the strong magnetic field and plasma environment of the Jovian magnetosphere produce a strong electrodynamic interaction between plasma and satellite.



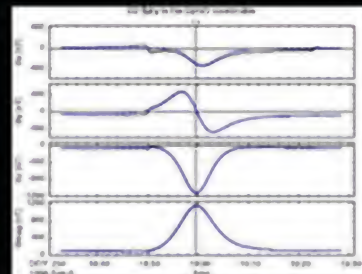
The Galilean satellites are unique because emissions from their atmospheres, produced by this interaction, have been imaged. Each has distinctive auroral emissions that provide a unique signature of the plasma interaction at the satellite.

Galileo discovery of Ganymede magnetic field



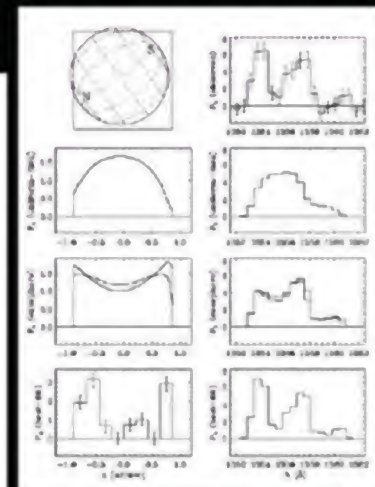
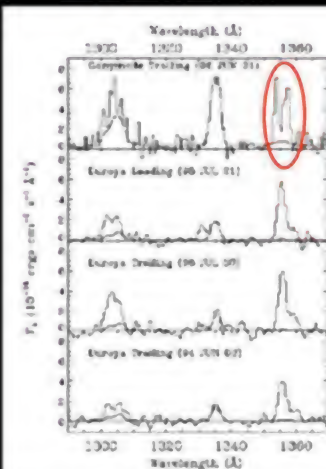
Gurnett et al. 1996
Kivelson et al. 1996

Strong magnetic field and considerable field rotation near Ganymede indicated the perturbations were Ganymede-associated.



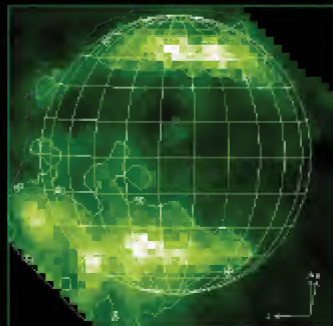
Detection of O₂ atmosphere

Hall et al. 1998

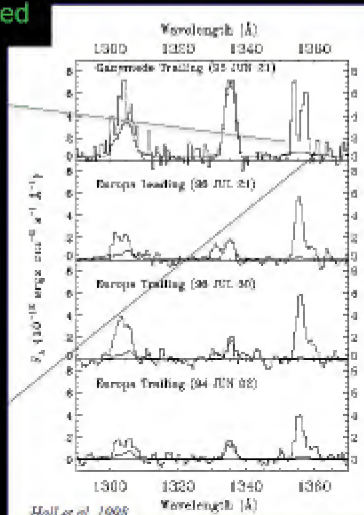


Aurora on Ganymede?

Aurora on Ganymede confirmed



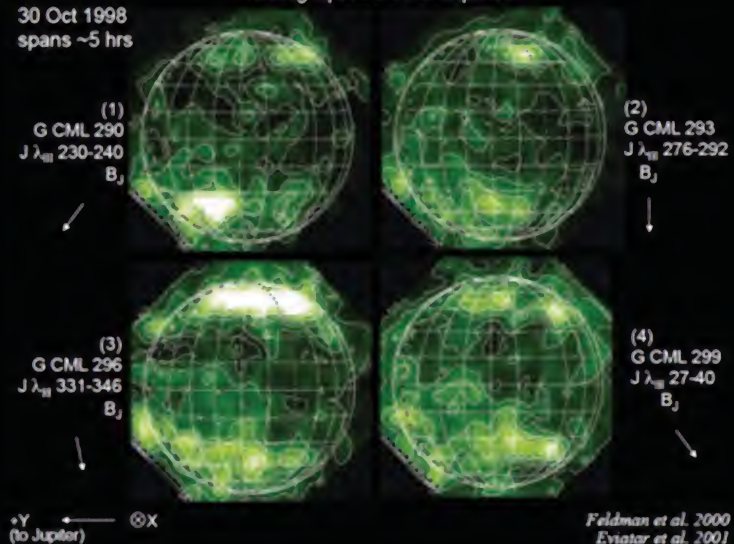
OI 1356Å emission
Feldman et al. 2000



Hall et al. 1998

30 Oct 1998
spans ~5 hrs

Trailing/Upstream Hemisphere

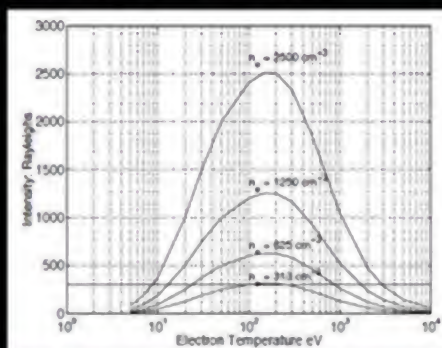


Feldman et al. 2000
Eviatar et al. 2001

Plasma population at Ganymede [Scudder et al., 1981]:

- thermal component $n_e \sim 5\text{--}20 \text{ cm}^{-3}$, $T_e \sim 20 \text{ eV}$ [$\sim 600 \text{ cm}^{-3}$]
- superthermal component $\sim 0.1 \times n_e \text{ cm}^{-3}$, $T_e \sim 2 \text{ keV}$ [$\sim 1000 \text{ cm}^{-3}$]

This plasma population can't produce the 300-400R observed.

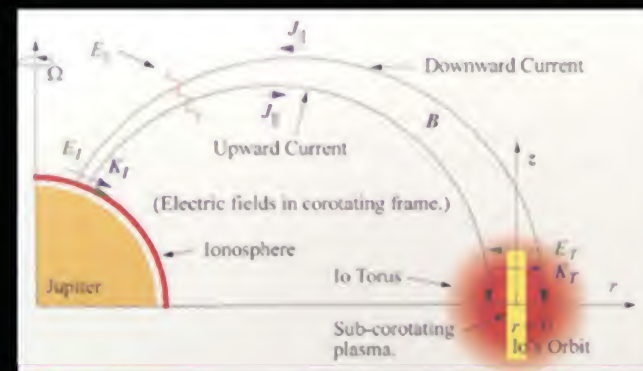


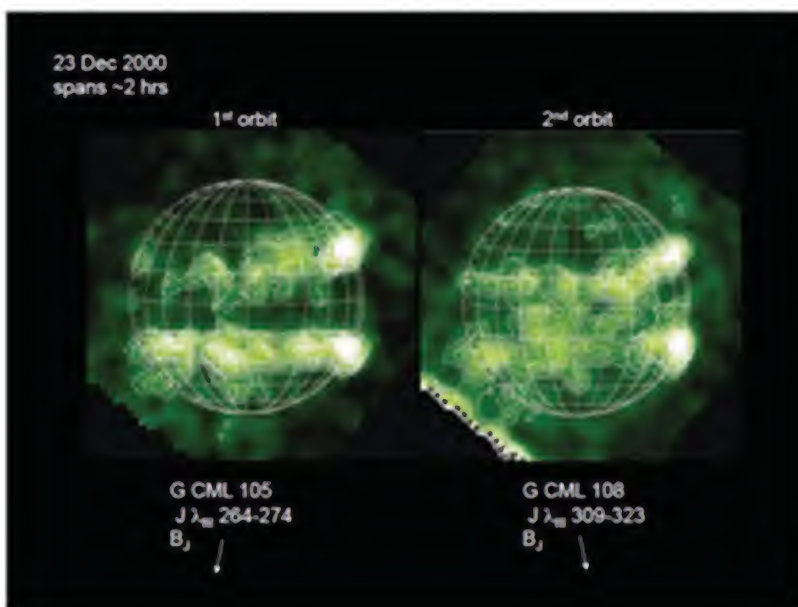
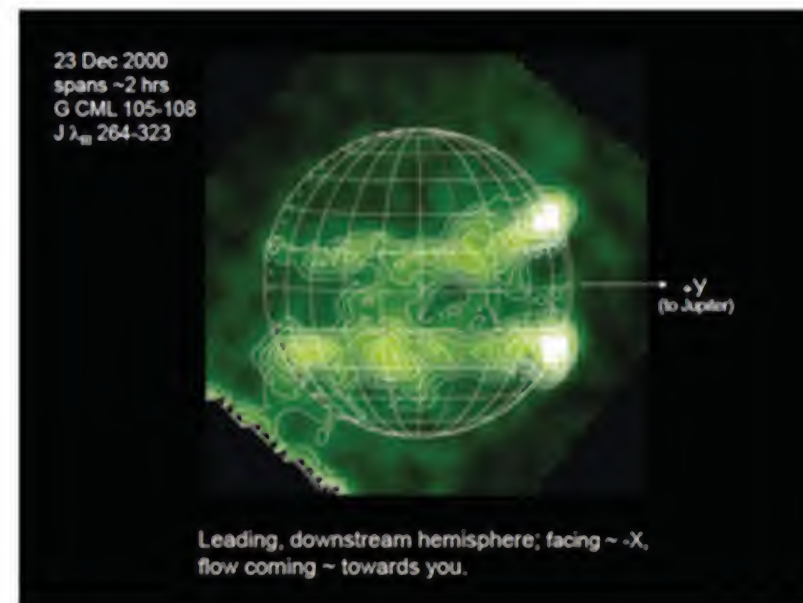
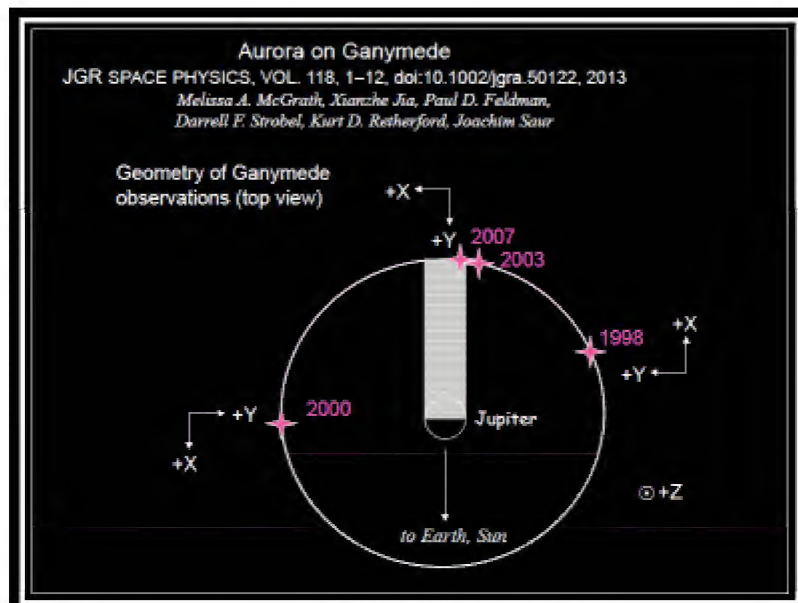
Eviatar et al. 2001

➡ Conclusion: Electrons must be locally accelerated

Two mechanisms proposed by Eviatar et al.:

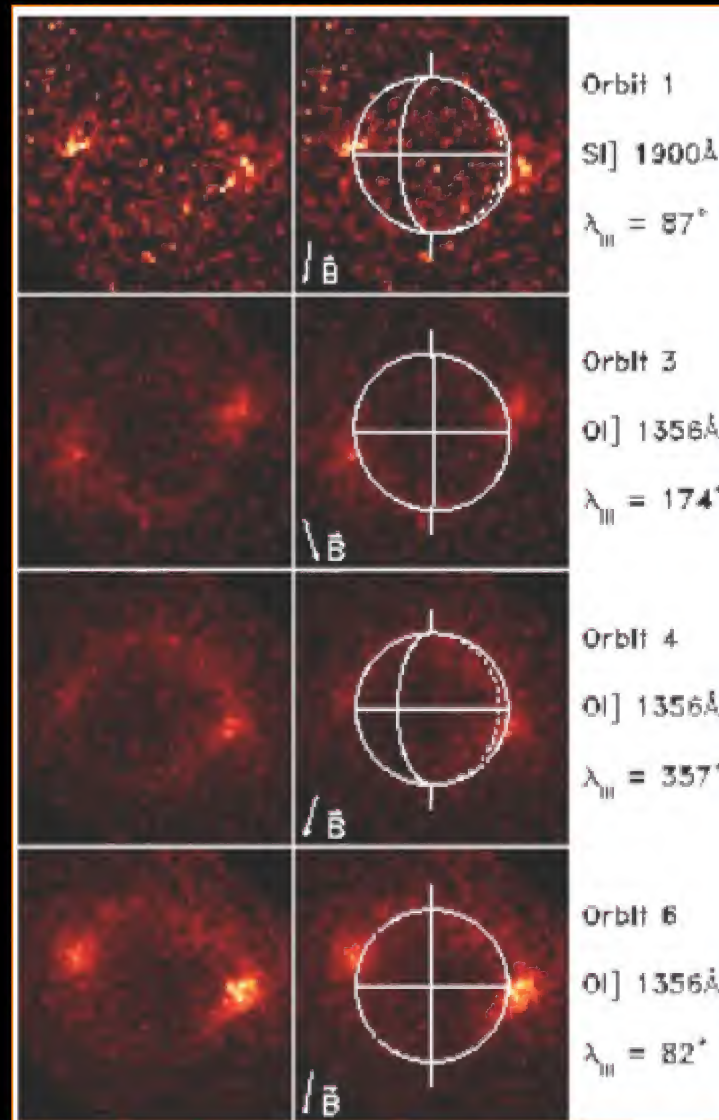
- stochastic acceleration by electrostatic waves
- Magnetic field-aligned electric fields and associated Birkeland-type currents produced by plasma flow past Ganymede (tapping Jupiter's rotational energy) – in analogy with Earth's aurora

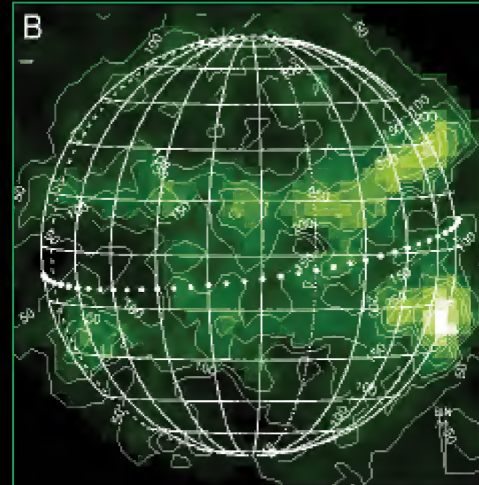
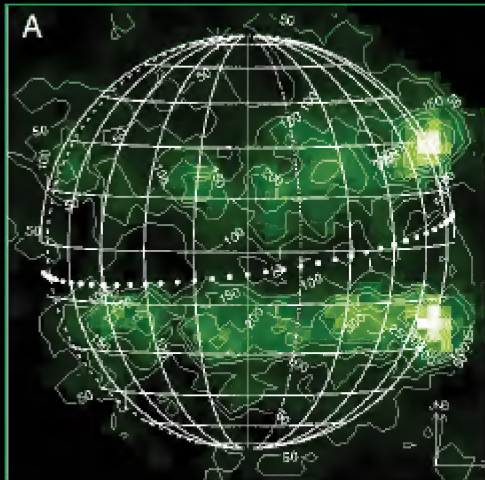




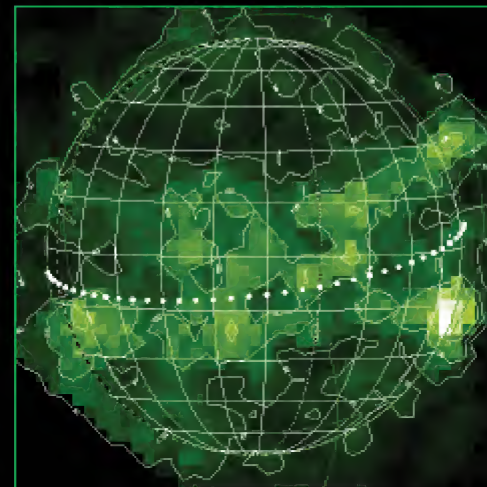
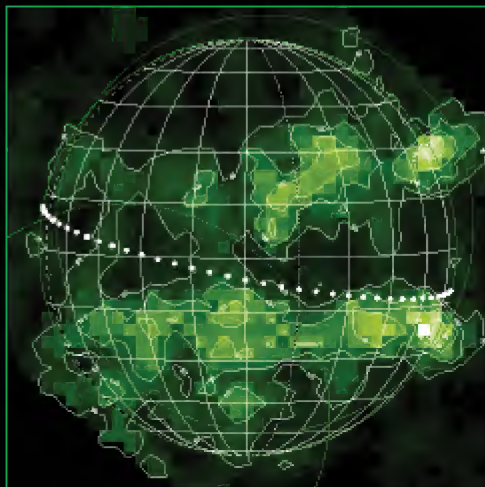
At Io, the auroral emission has a very different morphology: equatorial bright spots that rock with changing Jupiter B field orientation

Roesler et al. 1999





Ganymede B field
equator superposed

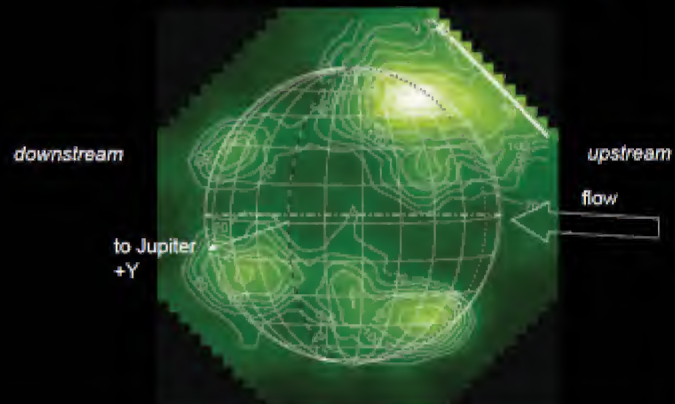


Jupiter B field
equator superposed

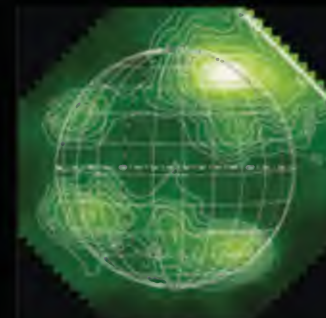
➡ Conclusion: Ganymede's auroral oval does not rock like Io's spots

30 Nov 2003
 spans ~2 hrs
 G CML 336-340
 J λ_{H} 220-288

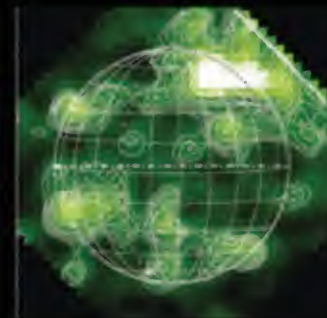
~Jupiter facing hemisphere; flow ~ from right to left



30 Nov 2003
 spans ~2 hrs



G CML 337
 J λ_{H} 220-232
 B_J



G CML 337
 J λ_{H} 220-232
 B_J

a second observation of the Jupiter-facing hemisphere was acquired in 2007

strikingly similar morphology to that seen in 2003 observation



~Orbital leading
 Downstream plasma



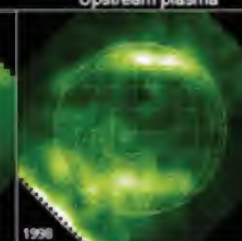
2000

~Jupiter facing
 Plasma flow right to left



2003

~Orbital trailing
 Upstream plasma



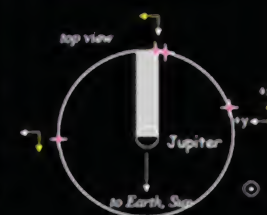
1998

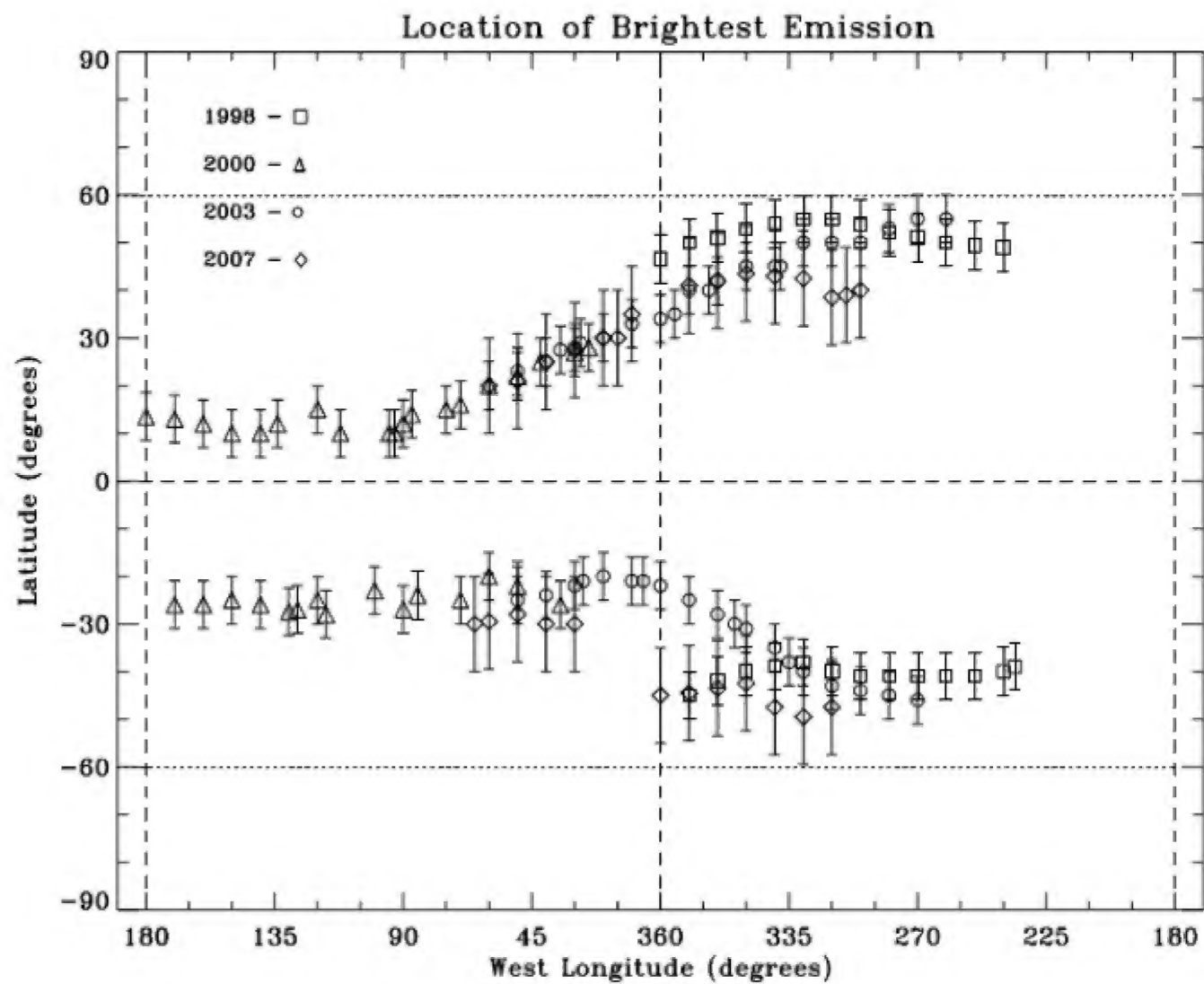
McGrath et al. 2013

Two more sets of observations of the leading hemisphere were acquired in 2012 by Saur et al. – they look almost identical to those acquired in 2000



2007

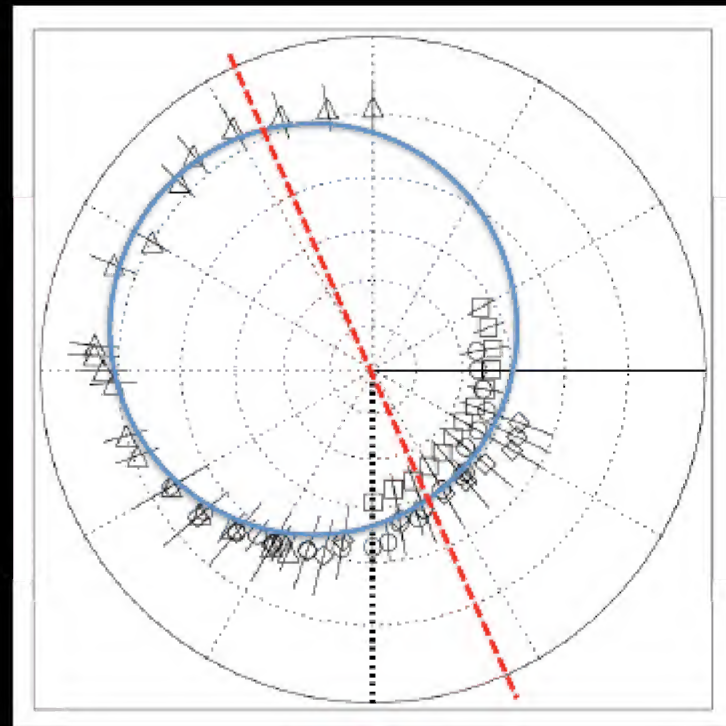
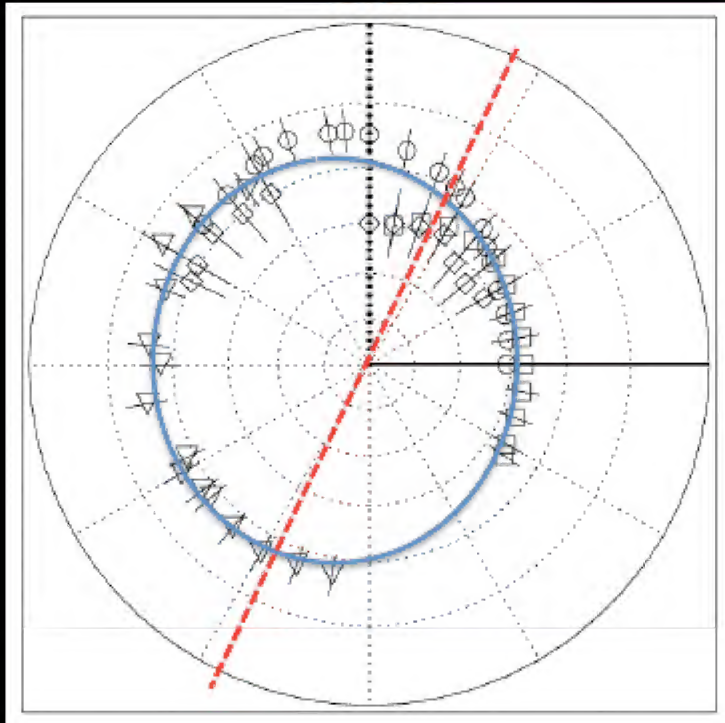




North pole projection

← plasma flow

to Jupiter



to Jupiter

Ganymede magnetic pole:
156°W, 86°N
336°W, 86°S

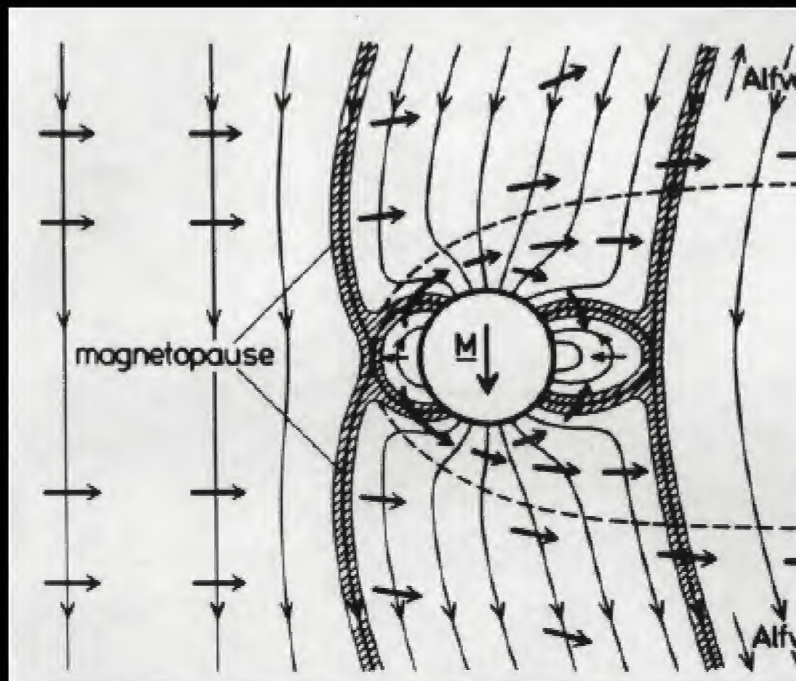
South pole projection

Summary of observed characteristics

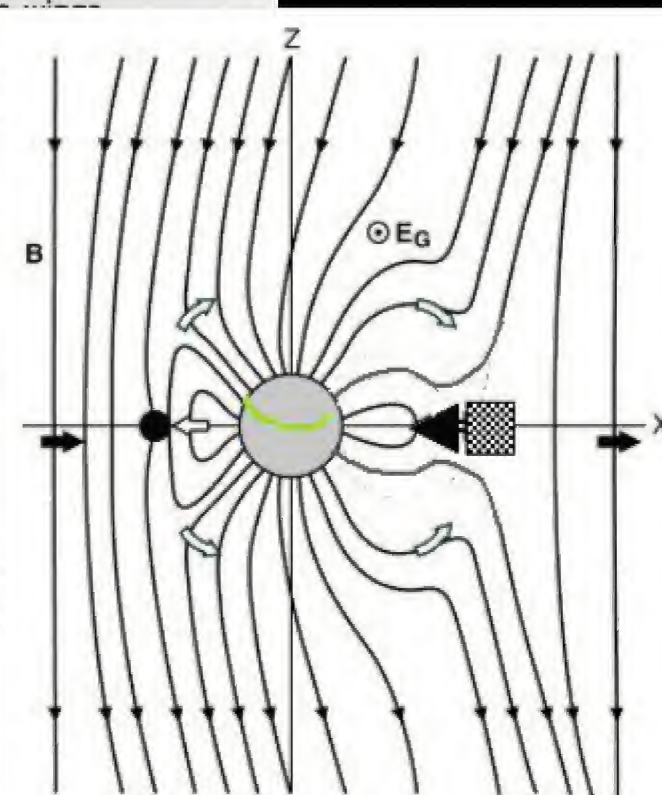
- The overall emission pattern is relatively stable with time.
- In the downstream hemisphere, the emission extends to significantly lower latitude in the northern hemisphere than the southern hemisphere.
- The opposite is true in the upstream hemisphere: emission is at higher latitude in the northern hemisphere than the southern hemisphere.
- The emission is not symmetric about either pole.
- The emission is not symmetric about the equator.
- The auroral oval is stretched in the downstream direction, more so in the N than the S.
- The auroral oval is not symmetric about the plasma flow direction. It appears to be roughly aligned with Ganymede's magnetic axis, especially in the north.
- Emission is always brightest near the NW (dusk) limb, followed by SW limb, then SE limb, then NE limb

Comparison with Models

- One proposed mechanism: Electrons accelerated by field aligned potentials at the boundary between Ganymede's open and closed field magnetic lines produce the auroral emission
- I will show you comparison between location of the open-closed field line boundary (OCFB) and the location of the auroral emission for several different models:
 - Khurana et al. (2007): vacuum superposition of Ganymede & Jupiter magnetic fields
 - Koop & Ip (2002): resistive MHD model
 - Jia et al. (2008, 2009): global 3-d single-fluid MHD model
- For all comparisons I will show models where Ganymede is ABOVE (in red), IN (in green), and BELOW (in blue) the plasma sheet



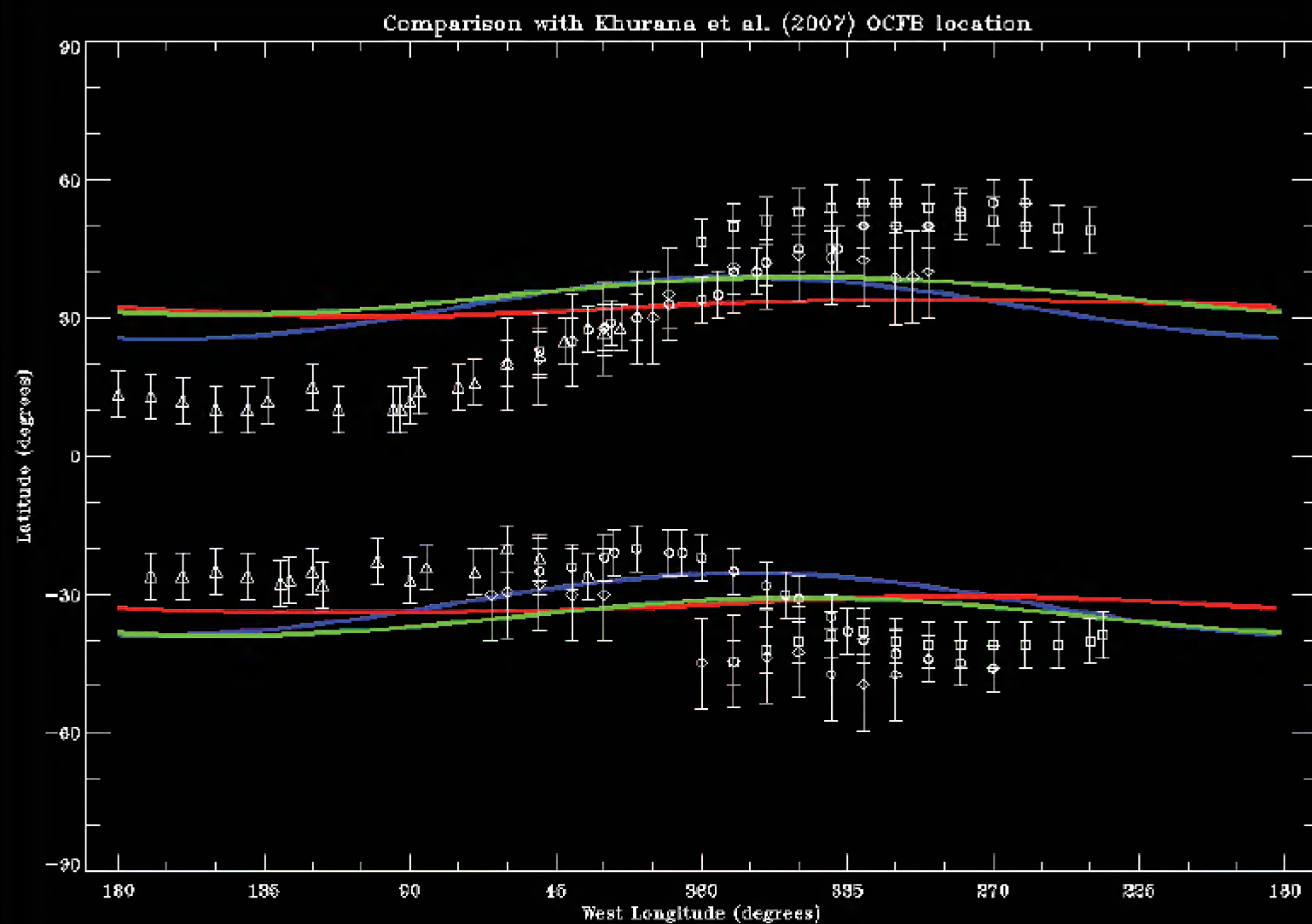
Neubauer 1998

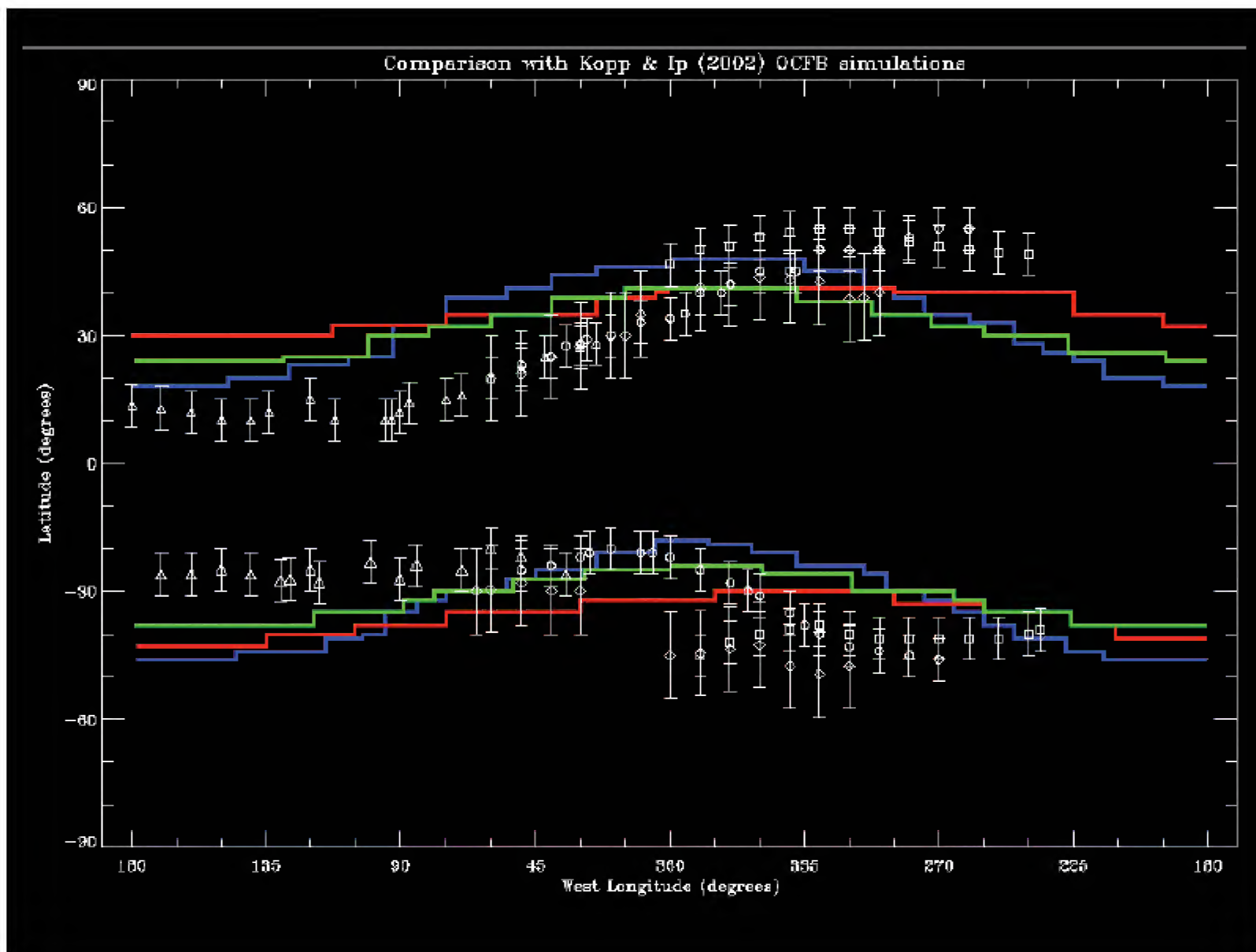


- ➔ Torus Plasma Flow
- ⇨ Ganymede's Magnetospheric Flow
- Upstream Reconnection Line
- ▨ Downstream Reconnection Line

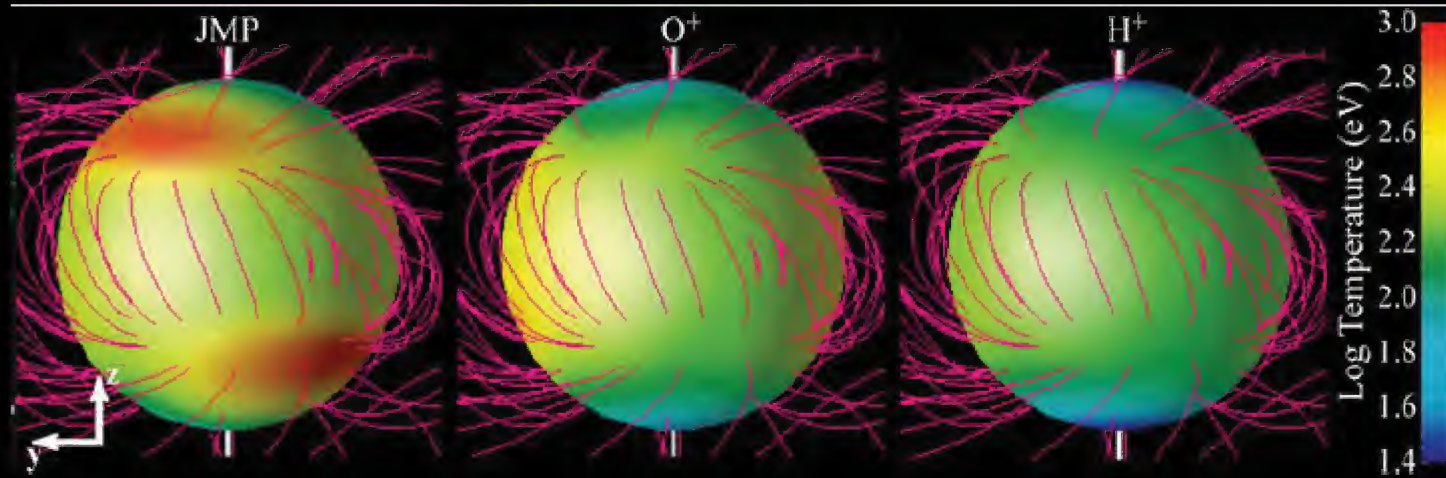
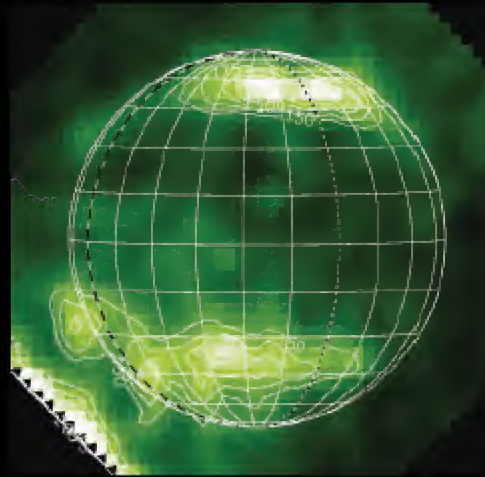
— open-closed boundary

Kivelson 2001

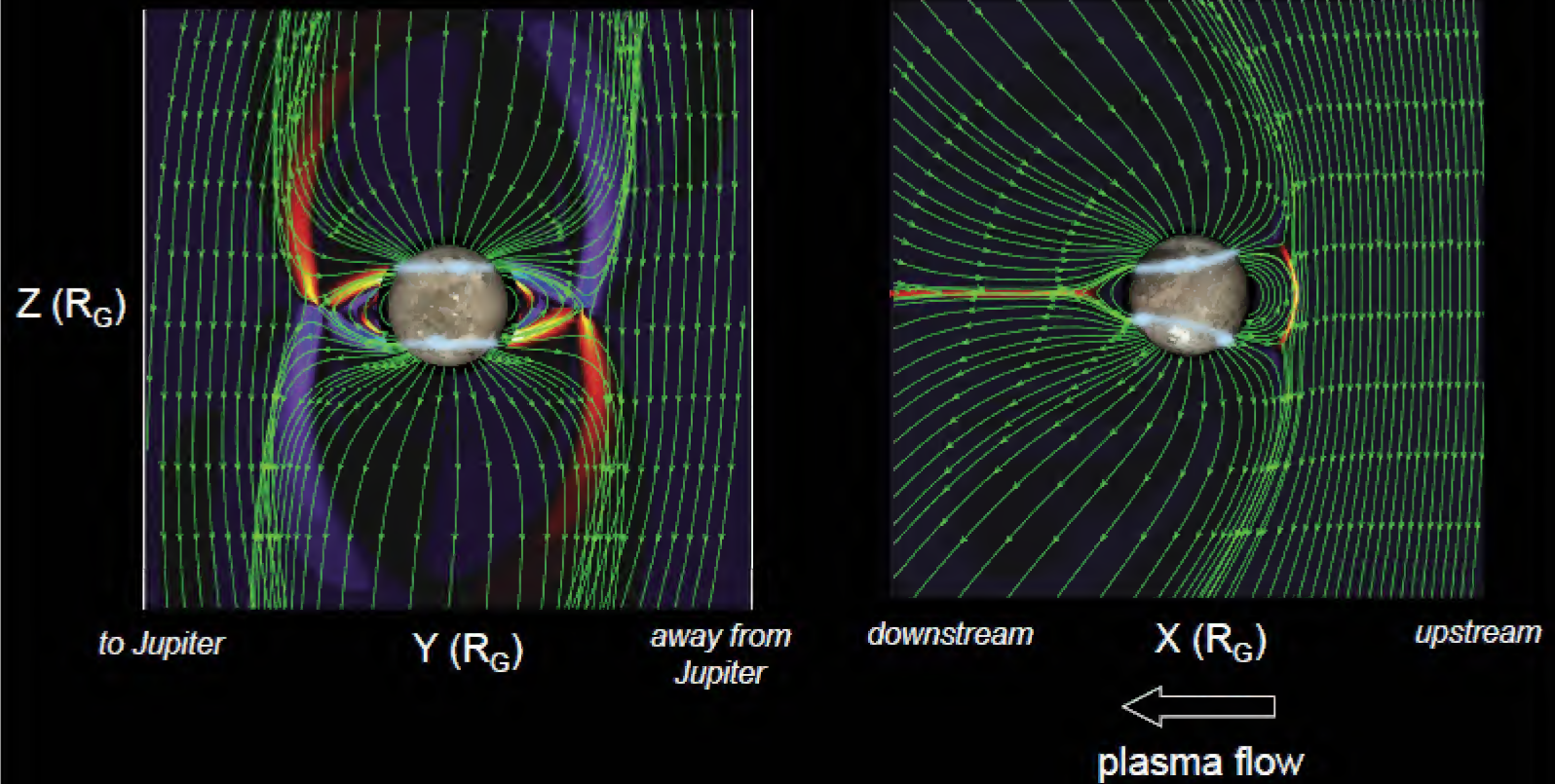




Paty and Winglee (2004)



Jia et al. 2008, 2009



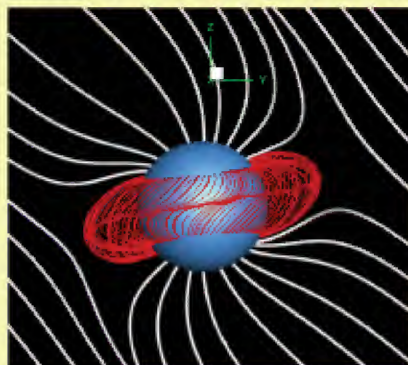
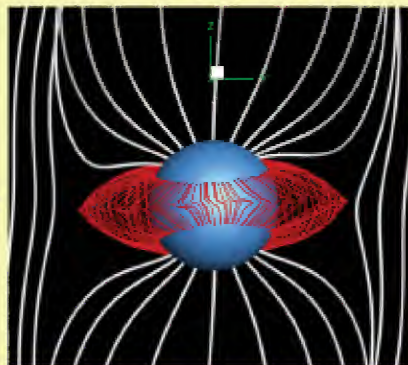
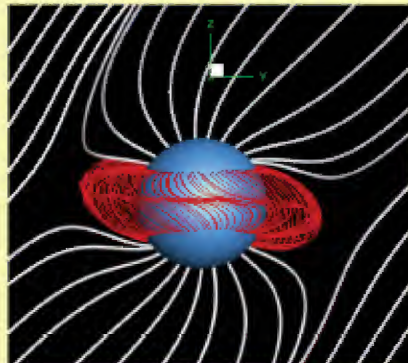
*Jia et al. 2008,
2009*

Ganymede is ABOVE
the central current sheet

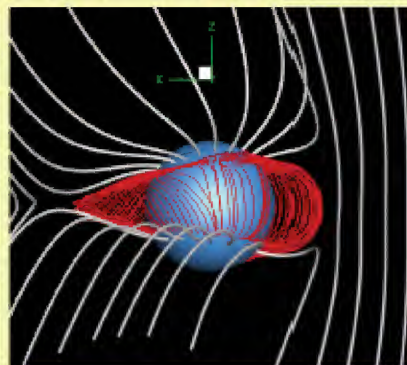
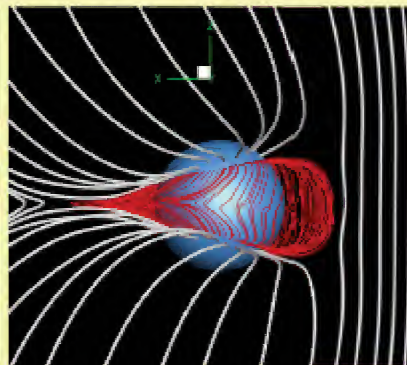
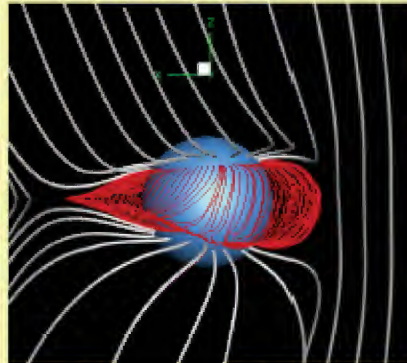
Ganymede is NEAR
the central current sheet

Ganymede is BELOW
the central current sheet

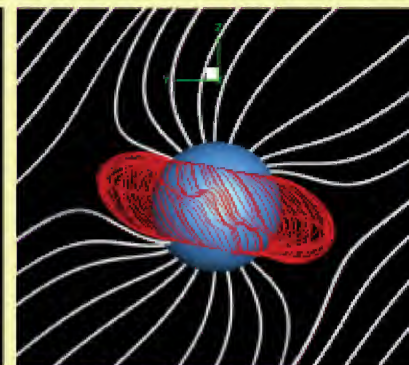
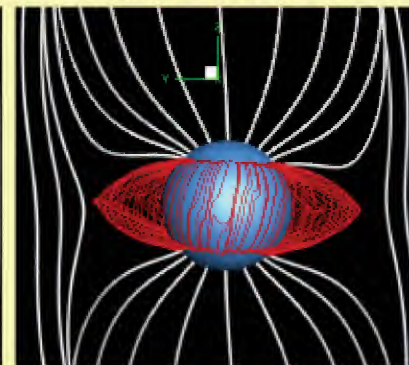
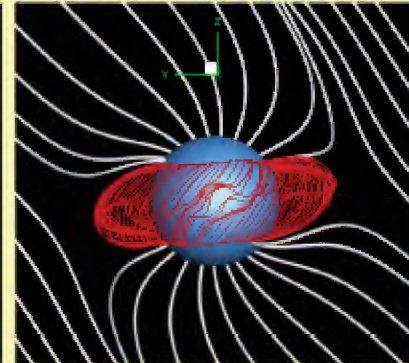
YZ plane
(viewed from downstream)

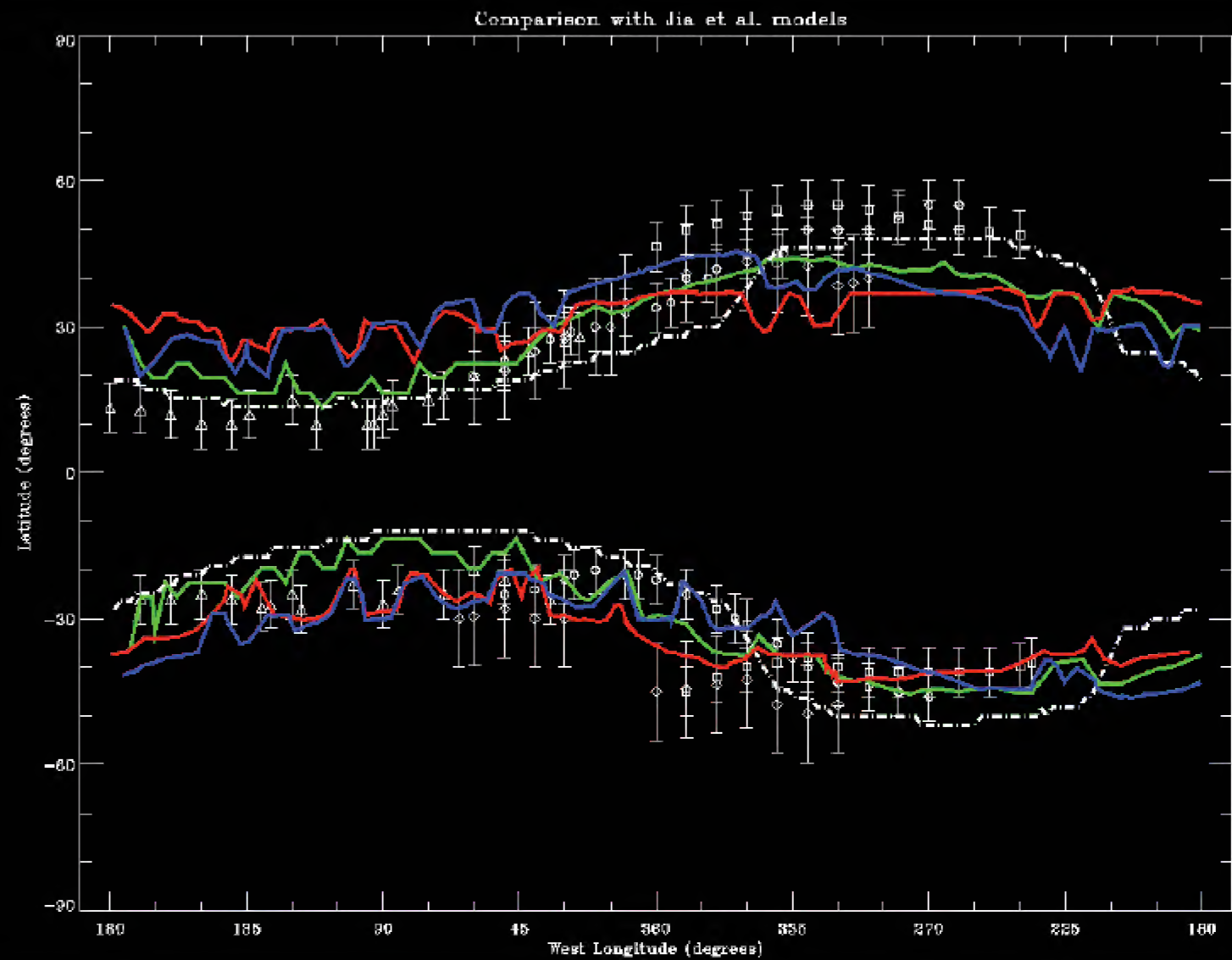


XZ plane
(viewed from Jupiter)

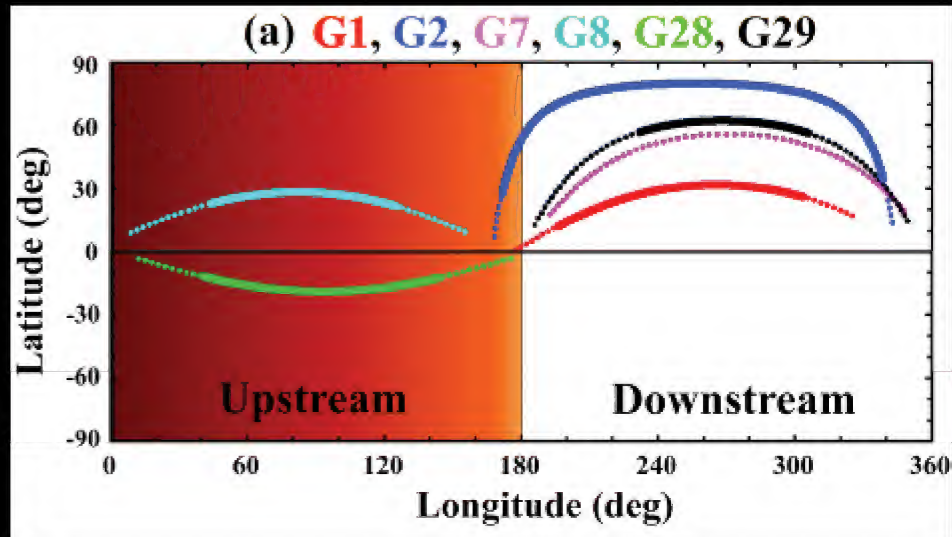


YZ plane
(viewed from upstream)

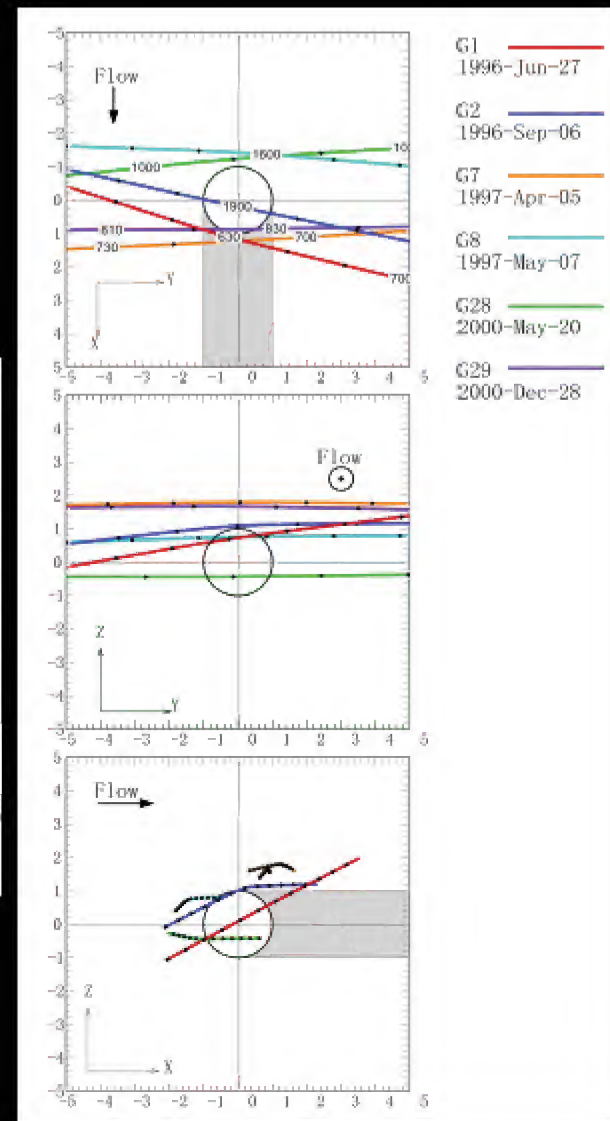




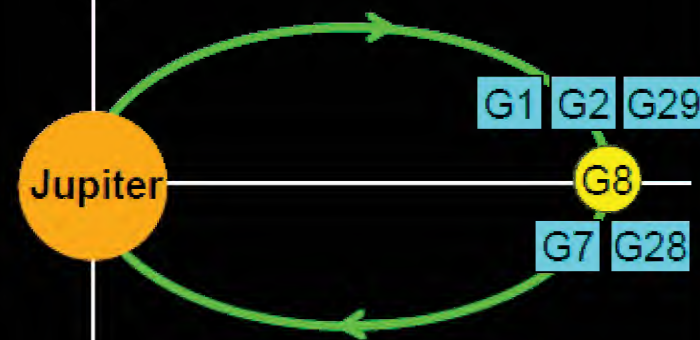
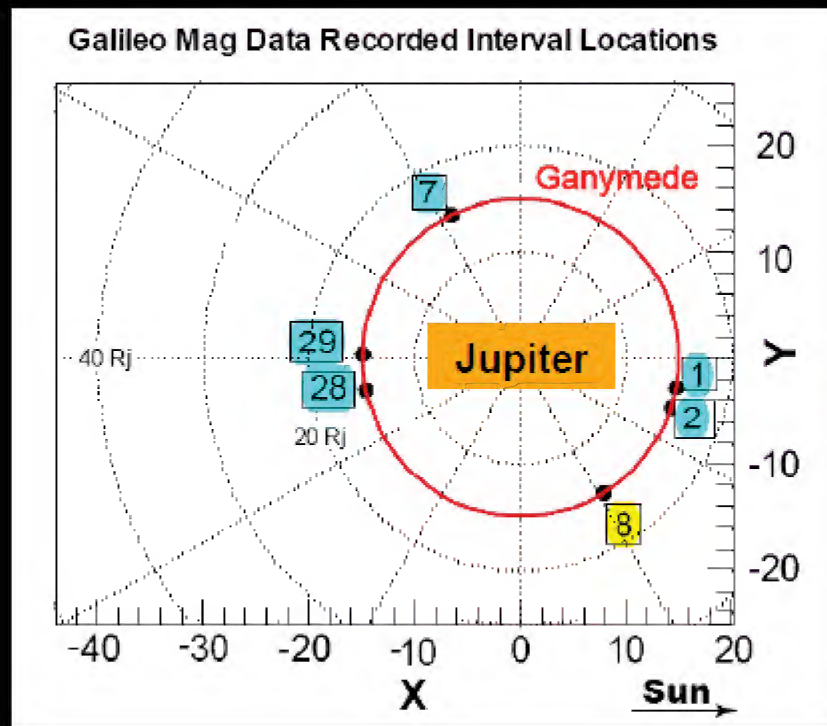
Locations of Galileo's six close encounters with Ganymede



Jia et al. 2009



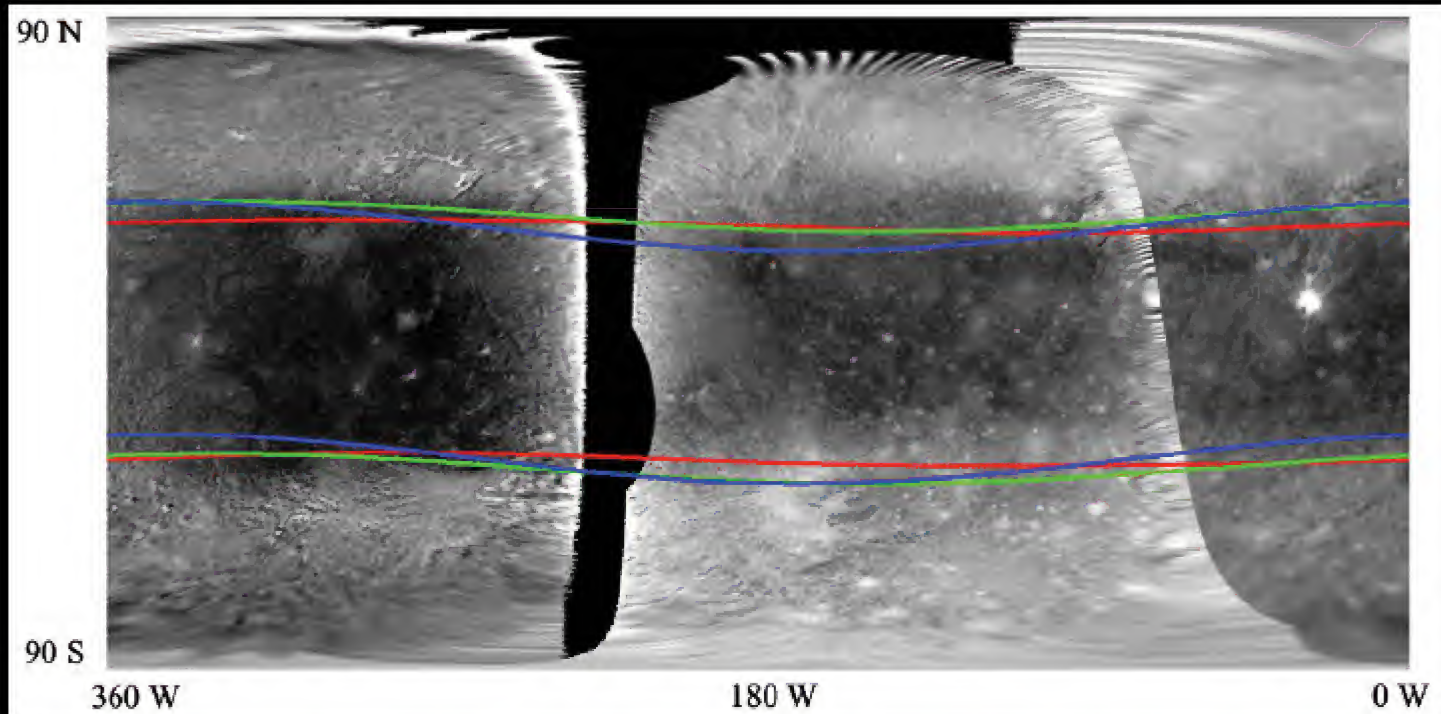
The six close encounters occurred in different local time sectors in Jupiter's magnetosphere and at different locations relative to the Jovian plasma sheet.



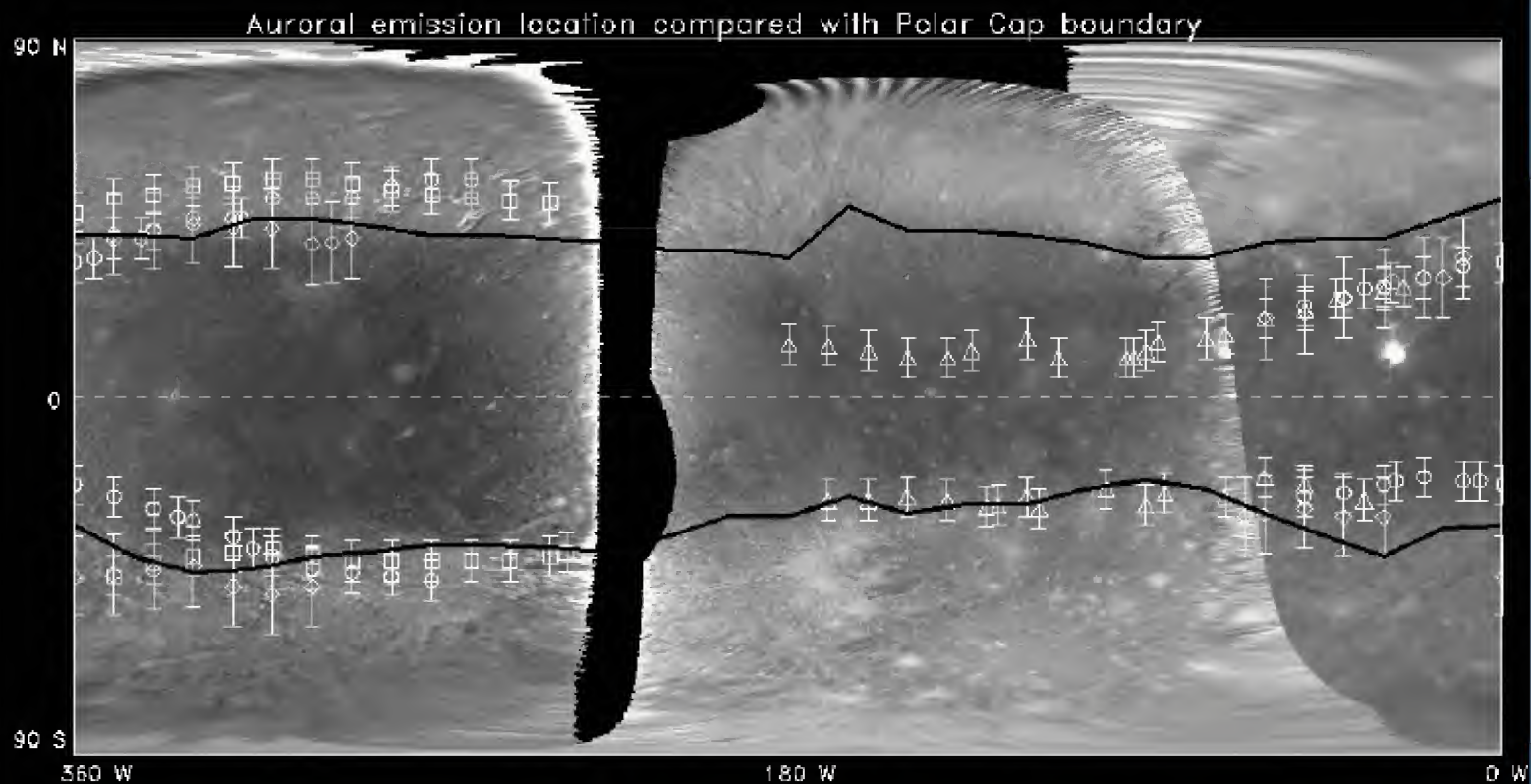
Ganymede has visibly brighter, bluer polar caps



Based on the apparently close correspondence between the OCFB of the Khurana et al. (2009) static superposition model with the polar cap boundary, they concluded that particle bombardment of the poles is the cause of the bright polar caps.



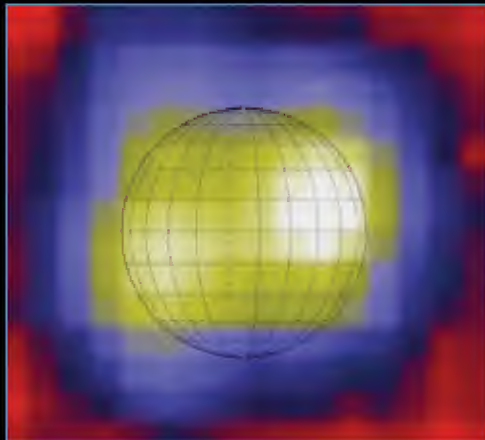
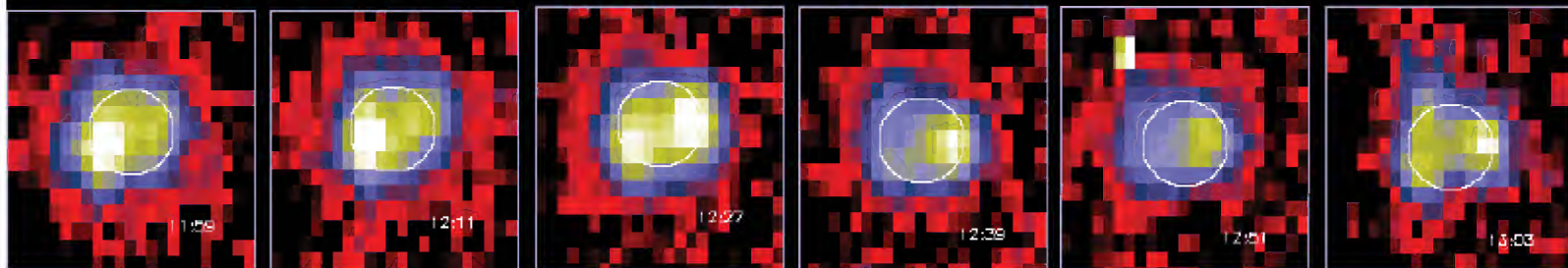
However, I just showed you the close correspondence between the OCFB of the Jia et al. model and auroral emission. Khurana model does not account for the interaction between Jovian plasma and Ganymede.



If the auroral emission corresponds to the OCFB, then neither the OCFB nor the auroral emission match the location of the polar cap boundary well in the northern hemisphere especially from 0° – 180° W longitude.

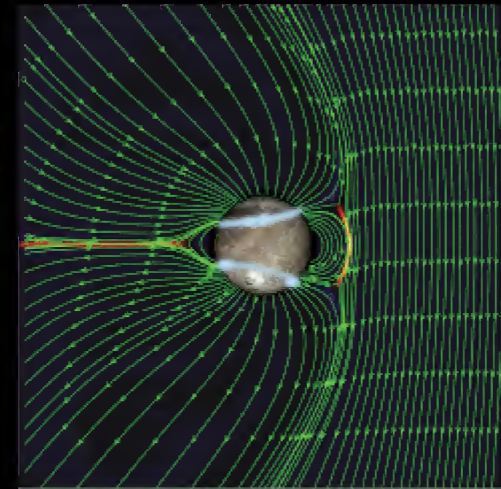
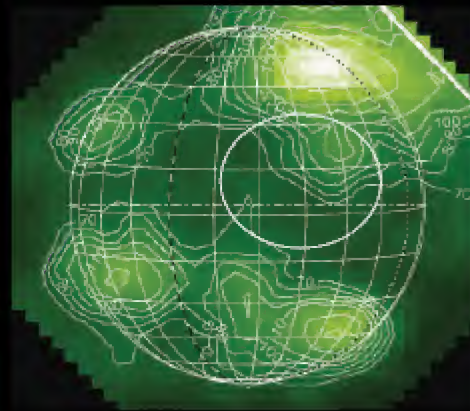
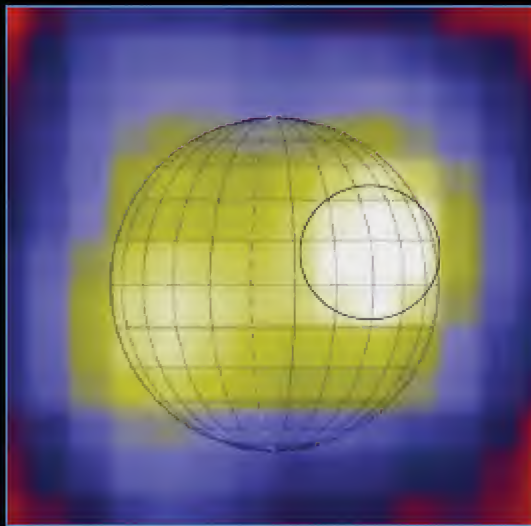
Unpublished Keck observation of *Ganymede* in eclipse (Jupiter-facing hemisphere - same as 2003 and 2007 UV observations) in oxygen 630 nm emission by Mike Brown:

- visible O emission is not at the poles, it is near the equator
- significant short-term variability



Composite spans ~ 1 hr, G CML 351, J λ_{III} 69-106

Comparison between visible and UV, almost the same (Jupiter-facing) hemisphere:



Jupiter facing hemisphere, plasma flow from right to left

Summary

- Ganymede has a stable, well-defined pattern of auroral emission: higher latitude on the upstream hemisphere, lower latitude on the downstream hemisphere. The northern oval is bigger than the southern oval.
- The emission pattern is reasonably well matched by the OCFB in the MHD models of Jia et al.
- Puzzling emission morphology has been observed in visible aurora that is inconsistent with the UV morphology.

